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Title	NUMERICAL APPROACH TO THE STUDY OF COASTAL BOULDERS: THE CASE OF MARTIGUES, MARSEILLE, FRANCE
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Abstract

The coastal strip that extends to the east of the city of Martigues, between the Anse de Bonnieu and that of the Chariot, is characterized by an alternance of gently rocky coast and 5 m high cliffs shaped in Miocene limestone. The foot of the cliff is marked by a deep notch and a discontinuous wave-cut platform; at its base, the sea bottom has a maximum depth of about 4,5-6m. The emerged area is marked by the presence of boulders up to 35ton in weight located up to about 10 m from the coastline and 2 m above sea level. A geomorphological survey was conducted by means of a Terrestrial Laser Scanner allowing to obtain a breakdown of the boulder sizes. The proposed study has focussed, in particular, to estimate the minimum wave height needed to detach and transport on the surf bench two boulders originally joined in a bigger one about 25 tons heavy placed on the wave cut platform. Hydrodynamic models developed by various authors were used to calculate the minimum wave height useful to move them. The data obtained from these different hydrodynamic equations were related to wave-climate data collected over the last 15 years by the buoy of Marseille in the Gulf of Lion. This study seems to confirm that a tsunami impact (never recorded in the last 20 years) would not have been necessary to move the two boulders. Hydrodynamic equations suggest that the boulder could have been broken and just after moved as a consequence of the impact of waves generated by an extreme storm occurred before December 2003; this seems to be in agreement with the morphology of the sea bottom, hydrodynamic features and eyewitness.

Keywords	sea storm, boulders, hydrodynamic equation.
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Suggested reviewers	Andreas Voett, Paolo Sansò, Hervé Regnauld

Submission Files Included in this PDF

File Name [File Type]

Author agreement Piscitelli et alii NEW.doc [Author Agreement Form]

Cover Letter Piscitelli et alii NEW.doc [Cover Letter]

Reply to the Reviewers Piscitelli et alii.doc [Response to reviewers]

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We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process.
He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Signed by all authors as follows:

Arcangelo PISCITELLI
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Jean-Claude HIPPOLYTE
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To Editors
Quaternary International

Dear Editors,

please find the new version of the manuscript titled: “Numerical approach to the study of coastal boulders: the case of Martigues, Marseille, France)” proposed for pubblication on Quaternary International and considered acceptable for publication with moderate revision; it has been improved according to all the suggestions of the two anonymous reviewers as we highlighted in the following pages.

Best regards

The Authors

Arcangelo PISCITELLI

Maurilio MILELLA

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Bari, May 20, 2016

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Reply to the "Comments from the editors and reviewers"

- Associate Editor

The paper is certainly interesting and complete but the organization of the text and English should be reviewed. It is also necessary to correct the many inaccuracies that Reviewers report. If all this is done the paper can definitely be published.

***Reply**: many thanks. The text has been completely re-organized following the suggestions of both reviewers; English form has been improved by a mother tongue.*

-**Guest Editor**

- Please revise the paper following advice and comments of the reviewer. In addition, please reduce number of figures to about 8. Please see text amendments in the abstract and follow this example for the remaining text.

***Reply**: many thanks. The text has been completely re-organized following the suggestions of both reviewers; the English form has been improved by a mother tongue.*

-**Reviewer #1**

- Excellent paper but the english needs to be checked and some parts are not totally clear I have added comments on the file when the text needs some improvement.

***Reply**: we would like to thank reviewer 1; his suggestions have permitted to rewrite the parts that were unclear and to improve also the English form.*

-**Reviewer #2**

The manuscript focuses on boulders occurring along the coast of Marseille (France) aiming to look for the process responsible for their deposition (tsunami vs sea storm) by means of geomorphological and Laser Scanner survey as well as hydrodinamic computations.

The manuscript is interesting and supplies a further step in the coastal processes knowledge. I can not find any relevant problem on the scientific content of the manuscript.

However the manuscript can not be published in its present form since I think that some problems should be solved as follows:

***Reply:** many thanks for your suggestions. All of them have been appreciated and accepted; they permitted to improve the overall quality of our contribution.*

1) English form

The English form is very poor and numerous mistakes can be found in the text so that a deep revision is needed

***Reply**: a mother tongue has improved the English form*.

2) Structure

1) Chapter 2 should contain more data about strata and joint pattern of bedrock since it strongly affects boulders carving.

Reply*: Requested data have been produced thanks to a new field survey performed by some of the Authors and by a specialist; as consequence Chapter 2 has been improved heavily and this requested the increase of the number of the Authors.*

2) In the Chapter 3 – Material and methods Authors should only describe material and methods used to develop research and shouldn't report here some results of survey. I would move these last ones to the following chapters, mainly in the reconstruction of boulders movement and discussion chapters.

Reply*: we did this.*

3) I think that Chapter 4 (reconstruction of the boulders movements) should be split in three chapter:

Chapter 4 : reconstruction of boulders movement

Chapter 5 : Hydrodynamic calculations

Chapter 6: discussion

Reply*: hoping to satisfy the pertinent suggestions received, we introduced a chapter (4) titled "Boulders and coastal features" and we separated the Chapter 5 - Discussion in three sub-chapter: "5.1 - Reconstruction of the boulder's movement, 5.2 - Hydrodynamic calculations, 5.3 - Wave analysis"*

4) The Conclusion chapter should be greatly improved reporting briefly the focus of research, methods used, the achieved results and final considerations.

Reply: *we completely rewrote the chapter "Conclusion"*

3) Bibliography

1) Authors should check references since some papers are reported in bibliography but not in the text (Bryant, 2001; Hall et al., 2006; Mastronuzzi et al., 2013; Morhange et al., 2006; Williams et al., 2004).

2) Other papers are reported in the text but not in bibliography (Mastronuzzi et al., 2006; Laborel et al., 1994; Julian & Anthony, 1996).

3) Mastronuzzi and Pignatelli is 2013 in the text and 2012 in the Bibliography.

4) In the bibliography it is reported Goto et al., 2010b, but there is only one!

5) Mastronuzzi et al. (2007) focuses on rocky coast evolution in a stable tectonic area in response to Middle-Upper Pleistocene eustatic sea level change without any reference to high-energy events so I think this reference is not necessary.

Reply*: we corrected and improved the "Bibliography"*

4) Figure

1) Captions contains numerous mistakes (hight for height; food for foot; narrow for arrow,…)

2) I would make an effort to realize drawings to show the geographical position of the studied area and of wave recorder buoy. Satellite photos are not very clear and without the name of main localities and scale are useless.

3) In the manuscript figures are attached separately but in the captions some of them are reported as parts of one single figure (for example fig. 3 is composed by photo A, B, C and D; fig. 7 is compound by a left and a right photo; fig. 11 is compoun by four photo). I would suggest Authors to submit figures as they should be printed.

***Reply**: we improved captions and figures and reduced their number*

Many thanks for all

The Corresponding Author
Giuseppe Mastronuzzi

NUMERICAL APPROACH TO THE STUDY OF COASTAL BOULDERS: THE CASE OF MARTIGUES, MARSEILLE, FRANCE

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Abstract

The coastal strip that extends to the east of the city of Martigues, between the Anse de Bonnieu and that of the Chariot (Provence, South France), is characterized by an alternation of gently rocky coast and 5 m high cliffs shaped in Miocene limestone. The foot of the cliff is marked by a deep notch and a discontinuous wave-cut platform; at its base, the sea bottom has a maximum depth of about 4,5-6m. The emerged area is marked by the presence of boulders weighing up to 35tons, and located up to about 10 m from the coastline and 2 m above the sea level. A geomorphological survey was conducted by means of a Terrestrial Laser Scanner allowing to obtain a breakdown of the boulder sizes. The proposed study has focussed, in particular, to estimate the minimum wave height needed to detach and transport on the surf bench two boulders originally joined in a bigger one about 25 tons heavy placed on the wave cut platform. Hydrodynamic models developed by various authors were used to calculate the minimum wave height necessary to move them. The data obtained from these different hydrodynamic equations were related to wave-climate data collected over the last 15 years by the buoy of Marseille in the Gulf of Lion. This study seems to confirm that a tsunami impact (never recorded in the last 20 years) would not have been necessary to move the two boulders. Hydrodynamic equations suggest that the boulder could have been broken and just after moved as a consequence of the impact of waves generated by an extreme storm occurred before December 2003; this seems to be in agreement with the morphology of the sea bottom, hydrodynamic features and eyewitness.

Key words: sea storm, boulders, hydrodynamic equation.

1. Introduction

In recent years, scientific debate on coastal dynamics has been focused on the effects of the impact of extreme wave on coastal areas and, as consequence, on the awareness that their impact is increasingly risky for all human settlements and the environment has increased in recent years. In fact, examples of the recent impact of hurricanes induced exceptional waves and of devastating tsunamis occurring in the last fifteen years underlines the fact that morphological effects cannot be underrated neither in purely scientific terms nor when applied to the Integrated Coastal Zone Management (ICZM) (i.e.: Mastronuzzi *et alii*, 2013). In particular, an important part of science that deals with coastal morphodynamics, tries to study large boulder accumulations distributed along the coastline of the Mediterranean basin as an attempt to reconstruct the sequence of the impact of high-energy events that place and distribute them along the coast (i.e.: Mastronuzzi and Sansò, 2000; 2004; Morhange *et alii*, 2006; Mastronuzzi *et alii*, 2006; 2007; Scicchitano *et alii*, 2007; Maouche *et alii*, 2009; Vött *et alii*, 2010; Mastronuzzi and Pignatelli, 2012; Shah-Hosseini *et alii*, 2013; Anzidei *et alii*, 2014; Biolchi *et alii*, 2016). The study of extreme waves impacting all along the coasts of the world over the past 25 years has led to assumption that boulder accumulation can be consequence of impacts of both storm surges and tsunamis (Mastronuzzi and Sansò, 2004; Goto *et alii*, 2007; Barbano *et alii*, 2010; Bourgeois and MacInnes, 2010; Regnauld *et alii*, 2010; Paris *et alii*, 2010; Richmond *et alii*, 2011; Jaffe *et alii*, 2011; 2012). Unfortunately, a methodological tool by means of which it is possible to ascribe, with absolute certainty, the origin of the accumulation of boulders or megaboulders to one event or another has not been still identified.

Considering sizes and shape of the boulders surveyed along the coast, many authors have developed hydrodynamic equations from real case studies to build a model that could be applicable to recognize the origin of their deposits (Nott, 2003; Noormets *et alii*, 2004; Imamura *et alii*, 2008; Pignatelli *et alii*, 2009; Nandasena *et alii*, 2011; Benner *et alii*, 2010; Engel *and* May, 2012). These hydrodynamic equations have been widely used by various authors to investigate the origin of past boulder accumulations in many coastal areas of the Mediterranean basin (i.e.: Mastronuzzi and Sansò, 2004; Shah-Hosseini *et alii*, 2013; Biolchi *et alii*, 2016).

In particular, the Mediterranean rocky coast of Southern France, in the coastal area of Martigues, near Marseilles (Fig. 1), is characterized by the presence of large boulders at various distances and elevations from the coastline. They testify the impact of exceptional wave(s) that were able to scatter inland boulders coming from the midtidal and subtidal zones (Vella *et alii*, 2011). The origin of the extreme events responsible for their transport and accumulation is unclear, despite a series of surveys conducted using classic and modern techniques, also digital. Shah-Hosseini *et alii*, 2013 have attributed them to exceptional storms that occurred during the Little Ice Age (LIA), although the possibility that it could be a consequence of multiple events, may be also tsunami, cannot be rule out. Particular attention has been focused on two boulders, "A" and "B", indicated by local people as derived from an original one, "C".

In a previous paper, Shah-Hosseini *et alii (*2013) using the wide presence of bio-encrustations as bio-indicators, reconstructed the four phases of the breaking and the transport of the initial boulder ("C" in this paper but M7 in the original one): ì - detachment of the original boulder from its initial intertidal position; ìì - a phase of submersion attested by the development of Vermetids on the *Lithophyllum bissoides* encrustation; ììì - breakdown into boulders, M5 (= "B") and M6 (="A") followed by the overturning of the latter; ìv - transport of the block to the supratidal zone. To confirm this geomorphological model by means of a digital and mathematical approach, a detailed laser scan survey of the two boulders and of the local topography was carried out jointly to the bathymetric survey of the coastal area immediately near them. This allowed us to: ì -accurately reconstruct the present size of the boulders; ìì - reconstruct their original shape; ììì – apply the wave hydrodynamic equations of various authors to test their validity on a case study of which the impacting wave is known to have been due to a storm; ìv - reconstruct the sequence of events responsible for the breaking, transporting and depositing of the boulders.

2. Geographical, geological and wave climate settings

The study described in the following pages has been performed in an area located between the Bonnieu bay and the Chariot bay, South of Martigues near Marseilles, along the Mediterranean coast of France (Fig. 1). The coastal area is oriented northwest-southeast; it is characterized by a gently sloping rocky surface shaped in a highly fractured bioclastic limestone.

This Burdigalian marine limestone (Colomb *et alii*, 1975) is characterized by bioclastic and conglomeratic pinkish calcarenite with *Chlamys*, *Ostrea* and *Pecten*, about 10 m of thickness overlying in discordance on Cretaceous (Urgonian) limestone. The outcrop is characterized by a high density of faults and fractures presenting rough stratigraphic joints separating 50 cm to 2 m thick layers. Limestone beds gently dip to the southwest (<10°). Despite a lack of apparent finite deformation this limestone is cut by well-defined sets of fractures (Fig. 2 and Fig.3). The fracture planes do not exhibit evidence of shear displacement so that they can be referred to as joints. These joints are predominantly perpendicular to the bedding (Fig. 2A and 2B) and together with the bedding joints cut the limestone in blocks with planar surfaces. Near the sea shore and under the water, the joints are largely open as a result of dissolution and abrasion of the limestone (Fig. 2C).

The coastal landscape shaping was conditioned by the presence of these joints and by sea action; the results is an alternation of surf benches, wave cut platforms and cliffs up to about 5 m high (Fig. 4). The surf bench (hereinafter SB) generally corresponds to an area directly flooded by broken waves that have stripped of the soil and the upper strata of the local stratigraphic sequence; inland it is limited by a step whose height corresponds to the strata thickness (Figs. 4A and 4B). In some limited areas a wave cut platform (hereinafter WCP) of various extent is shaped in continuity with the SB from which it is separated by a very low step that it's not higher than 1 m. Locally, a short WCP corresponding to the strata surface is also present to the base of the cliffs that on their part, are engraved by the presence of a continuous notch up to about 2 m deep and 1 m high (Figs. 4C and 4D). The emerged area is marked by the presence of hundreds of large boulders with a maximum size of about 35 tons, positioned up to 10 m from the coastline and at about 2 m above sea level (Fig. 3 and 4A) (Vella *et alii*, 2011; Shah-Hosseini *et alii*, 2013).

The French Mediterranean basin is considered to have been a moderately active tectonic zone during the Holocene (Vella *et alii*, 1998; Vella and Provansal, 2000; Jolivet *et alii*, 2008). Tsunami-generating earthquakes have rarely been reported by the Bureau de Recherches Géologiques et Minières – BRGM (www.ngdc.noaa.gov). Its archives report the occurrence of 14 tsunamis since1755, highlighting the occurrence of only one destructive event which occurred on 27 June 1812 (4 on the Sieberg-Ambraseys intensity scale), when boats and infrastructure in the old port of Marseilles were damaged. The event may have been recorded in the accumulated boulders in the area of Martigues; in fact 14C ages obtained on some bio-encrustations from different boulders seem to suggest a sequence of different high-energy wave impacts distributed over the past 700 years (Vella *et alii*, 2011; Shah-Hosseini *et alii*, 2013). Some 14C ages seem to fit in a period that comprises the 1812 event; on the other hand, the obtained range of ages, from 1660 to1860, in a period corresponding to the LIA during which it is normal to suppose the occurrence of important storm events able of scraping and moving boulders inland (i.e.: Kaniewski *et alii*, 2016 , for the Central Mediterranean zone). Minor tsunami events have been recorded in historic and modern times on the French Riviera coast about 150 km east of Martigues. They were probably triggered by submarine landslides but no geomorphological evidence have been recognized (Julian *and* Anthony 1996).

Based on the present knowledge, there is no evidence that leads to correlating the surveyed boulders to the impact of a tsunami rather than that of a storm. However, it is also possible that storms that characterize this stretch of coast, since their energy maybe able to move large boulders.

The surveyed coast is exposed to S-NW winds and the fetch is between 400 to about 600 nautical miles, even if protected by the Balearic Islands. Available wave data sets on the French Mediterranean coast are of limited durations. These data derive from the buoy placed in the Gulf of Lion, France (Fig. 5). The data collected, for a total of 1534 events, represent wave heights, period and direction only for waves with heights > 3m, in the period 1993-2008 (Tab.1). Table 2 shows the highest waves and their provenance direction, recorded by the buoy in the same period for each year.

3. Material and methods

A geomorphological and structural survey was conducted on the entire coastal area of Carro where boulders have been detected (Vella *et alii*, 2011; Shah-Hosseini *et alii*, 2013). To characterize the structural features of the area, joint planes in four areas have been measured directly in the field (Fig. 3).

Particular attention was paid to a limited portion (25m x 25m) of the coastal area, because of the presence of two boulders in the following pages named “A” and “B” The detailed terrestrial laser scan (hereinafter TLS) survey of this area was carried out using the Leica Scan Station 2 that has been operated jointly with a digital ground position system (hereinafter DGPS) Leica 1230 (Fig. 6). The scanner consists of a laser beam generator, a mirror rotating on its horizontal axis and forming a 45° degree angle with the beam direction at the same time rotating around its vertical axis. These features together permit to obtain a scan of an area extending 360°x270°.

To obtain a complete coverage of the surveyed area, a scan density of 3 mm was carried out from different positions along horizontal and vertical planes; different surveys have been joined and overlapped using targets to georeference all the points scanned from different positions to make possible a 3D reconstruction of the surveyed objects included in a “point clouds”. So, to obtain a 3D modelspace, it is necessary to overlap numerous scans in which target georeferenced by means of a DGPS were captured from different point of view. The post processing was performed using Cyclone 6.03 software; the point clouds obtained from each scan were linked together through the overlapping of different TLS scans. The next step was to isolate millions of points representing boulders “A” and “B” from the cloud points that comprise all the landscape and to reconstruct the original boulder “C” by matching them along the surface of fracture. The use of TLS techniques permit to reduce significantly the overestimation of the sizes and weight of the surveyed boulders respect to the handmade measurements; obviously this permits to use the hydrodynamic equations with major confidence (Marsico *et alii*, 2009; Hoffmeister *et alii*, 2013).

For completion of the sub-aerial survey, in the area of the “A” and “B” boulders, a specific bathymetric survey was performed during both ARA and snorkeling dives. They were performed by drawing nine different bathymetric transects starting from the biological mean sea level up to bathymetry 6m; depths and immersion times were recorded by a scuba computer SCUBAPRO Aladin 2G. This methodology allowed to reconstruct a 3D sketch of the morphology of the continuity of emerged coastal area and of the seabed up to about 50 m from the coastline (Fig. 7).

4. Coastal and boulder features

The rose diagram of the 111 measured joints shows that two main trends prevail: NNW-SSE to NNE-SSW and ESE-WNW (Fig. 3b). In detail, seven joints sets can be distinguished from this rose diagram: N160E, N170E, N5E, N20E, N30E, N115E and N130E (Fig. 3b). Taking into account that the Marseilles area underwent N020E and N165E compressions during the Miocene (Hippolyte *et alii*, 1993) the NNW- to NNE-trending joints can be interpreted as tension or shear joints formed during the alpine compressional phases (late Cenozoic). In contrast the ESE-trending joints are filled with Miocene shells and sand suggesting early formation (Burdigalian).

Schmidt diagrams of joints (Fig. 3d, e, f) show that the four studied areas are characterized by at least two perpendicular joint sets which allowed the separation of limestone blocks (NNE-SSW and ESE-WNW). We mapped the joint sets in the four areas along the coast using high resolution (15 cm) aerial photos (Fig. 3). Areas 1 to 3 are characterized by closely spaced NNE-trending joints and by numerous transported blocks (Fig. 3d and 3e). In contrast, area 4 is characterized by far fewer NNE-trending joints and transported blocks. The dense joint patterns in areas 1 to 3 probably facilitated the rock detachment.

As indicated above, the coastal area shaping has been driven by the sea action on a lithological sequence heavily conditioned by the presence of these joints. Surf benches, wave cut platforms and cliffs alternate between Carro and Bonnieu (Fig. 4). Regarding the sea bottom, its first 50 m has a maximum depth that ranges from 4 to 6 m. In general the surveyed area shows a double trend: starting from the coast line up to a depth of about 1.5 m it has quite a flat surface of varying extension corresponding to the wave-cut platform; a rapid increase of the slope up to 5-6 m deep indicate the passage to a gently sloping surface towards the higher depths.

Generally, boulders are distributed on the surf bench; boulders “A” and “B” are 7 meters apart at about 2 m above sea level, placed on the SB, slightly leaning against a step whose height corresponds to the strata thickness (Fig. 4). The details that characterize the geometric features of all three boulders were obtained from the scanned point clouds that permitted to obtain approximation within a few centimeters. The software used also permitted the reconstruction of the boulder “C” as result of the virtual rotation and shift of the boulders “A” and “B” (Fig. 8). All the geometrical parameters of boulders “A”, “B” and “C” were obtained by laser scanner software, given the very irregular shape of both blocks. The measures of three axes, the planar *a* (maximum) and *b* (medium) ones, the vertical *c*-axis, the volumes and weights are reported in the synoptic Table 3.

Both boulders (Fig. 9) show bio-encrustations that are typical of the base of the midtidal zone represented by the *Lithophyllum byssoides* rim, algae characterizing the lowest limit of the biological sea level (Laborel *et alii*, 1994; Morhange and Marriner, 2015). But mainly, boulder “A” shows a side characterized by the presence of a concavity that seems to correspond to an abrasive surface originally placed in the correspondence of the mean sea level. This geomorphological element confirms the initial position of the boulder "C" in correspondence of the mean sea level.

The cover of the carbonate algae appears partially colonized by *Vermetus triqueter*; this gastropod develops in the subtidal zone and the upper limit of the population which approximately marks the biological sea level (Laborel *et alii*, 1994). Its presence with some specimens of *Lithophaga lithophaga* suggests a lowering of the original position of boulder "C". Finally, the presence of *Barnacles* sp. can be related to the permanence of the boulder in the surfing area. Boulder "A" is overturned compared to the original verticality of boulder "C" as confirmed both by the morphological evidence and by the presence of the *L. byssoides* rim on its lower face. Furthermore, the rim indicates, with absolute approximation, the boulder's past interface with the mean biological sea level. On the other hand, boulder "B" is rotated, compared to the supposed original position of boulder "C"; this is evidenced by the particular aspect of the breaking surface that faces west (Figs. 9A-D), and is in the opposite direction of boulder "A". Boulder "B" is in the natural polarity as evidenced by the presence of the *L. byssoides* rim on its upper surface corresponding to the ancient surface below sea level.

The joint geomorphological and laser scan survey of the entire coastal area, emphasized the presence of two fracture systems (Fig. 2 and Fig. 3). Also considering the general structural features, and according to them, the first one is oriented NE-SW, almost perpendicular to the coastline and the second is oriented WNW-ESE, quite parallel to the coastline. These two alignments and the general one of the coastline, allowed us to hypothesize the original position and orientation of boulder "C" and the individuation of the detachment zone, located on the WCP about 12 m south of the present position of boulder "B", between two evident fracture lines (Fig. 10).

5 - Discussion

5.1. Reconstruction of the boulder's movement

The set of morphological and biological data and the bathymetric survey suggest a first reconstruction of the possible succession of the dynamic events that led the two separated boulders to the current position on the rocky surface. It was possible also taking into account the virtual reconstruction of boulder "C" obtained by the TLS survey.

The general shape of the latter and the presence of a quite continuous concavity along one of their side indicate an original position in correspondence of the mean sea level at the external sea side border of the surf bench. The extensive presence of *L. bissoides* on the top of boulders "A" - at present overturned - and "B" suggests that as consequence of numerous and repeated wave impact the boulders "C" collapsed depositing itself on the WCP, and eventually below sea level. Here it did not break as there is no evidence of marine organism colonies on its fracture surface. Only at a later time, after colonization by vermetids, the boulder “C” was broken in two blocks, “A” and “B”, without there having been the time to colonize the fracture by marine organisms before a new phase of movement. In fact, the resulting boulders were moved separately inland from the WCP to the current position on the SB just after have been broken during a following storm impact. Bio-indicators and morphological aspects in particular, provide evidence that during the movement, boulder “A” was scattered inland while overturning and, boulder “B” migrated inland, rotating approximately 90° anticlockwise (Fig. 11).

5.2 Hydrodynamic calculations

The data set can be analyzed to prove this sequence of morpho-events using also a numerical approach. In this way it is possible to define a morphodynamic sequence recognizable in a morphosequence. The features of the waves responsible for the initial detachment and inland transport of these two boulders can be characterized by applying the Pignatelli *et alii* (2009) hydrodynamic equations, considering the possible scenarios (Nott, 1997; 2003) that characterized the previous history as: ì - boulder “C” was in a Joint Bounded Scenario (JBS) at the external border of the SB facing to the impacting waves; ìì- the same boulder was disarticulated and then collapsed on the WCP but it remained here in its integrity; ììì-, the two parts in which boulder “C” was broken, moved separately but may be at the same time from the WCP to SB due to waves impacting in a Sub-aerial Boulder Scenario (SBS). Apparently this seems to be a wrong scenario; in effect, after the collapse, during the phase ìì and ììì, the boulder “C” was below the sea level in condition of wave’s absence but alternately in an emerged and submerged position in function of the breaking wave features during the storm. As consequence, due to the low water level of the wave-cut platform, and the behavior of and impacting waves of a strong storm on a WCP, a SBS was considered to explain the movement that split boulder “C” in “A” and “B” and finally deposited both on the surf bench. Assuming these aspects when applying the Pignatelli *et alii* (2009) equation, possible wave heights (Hs) were estimated:

- **JBS** for Boulder “C” $\mathbf{H_s}= (2*c*(\gamma_d-\gamma_w)/\gamma_w)/C_l$
- **SBS** for both Blocks “A” and “B” $\mathbf{H_s}= (2*(b*(\gamma_d-\gamma_w)/\gamma_w-2*(C_i*u_i)/g))/((b/c)*C_l+(c/b)*C_d)$

where H_s is the storm wave height at breaking point, *c* is the minor axis, *b* is the medium axis, γ_d is the density of boulder, γ_w is the density of water, C_l is the lift coefficient (Einstein and Samni, 1949), C_d is the drag coefficient (Helley, 1969), C_i is the coefficient of inertia (Noji *et alii*, 1985), *g* is the constant of gravity and u_i is the instant acceleration wave (Nott, 1997; 2003).

Other hydrodynamic models were tested in order to compare the possible resulting values of wave heights (Tab. 5). We applied formulas by:

a - Engel and May (2012) (*V* is the volume, *a* is the axis major, *α* is the slope of the coast and*q* is a empirical volume coefficient):

- JBS for Boulder C $\mathbf{H_s}= 2*(\gamma_d-\gamma_w)*V*(\cos\alpha+u_i*\sin\alpha)/(\gamma_w*C_l*a*b*q)$

- SBS Rampart for both Blocks A and B $\mathbf{H_s}= 2*u_f*V*\gamma_d/(\gamma_w*C_d*a*c*q)$

b - Nandasena *et alii* (2011), (*u_s* is the coefficient of static friction):

- JBS for Boulder C $\mathbf{H} = [(2*(\gamma_d/\gamma_w–1)*g*c*(\cos\alpha+u_s*\sin\alpha)]/C_l$

- SBS Sliding for Block B $\mathbf{H} = [(2*(\gamma_d/\gamma_w–1)*g*c*(u_i*\cos\alpha+\sin\alpha))/(C_d*(c/b)+u_sC_l)]/\delta g$

- SBS Overturning for Block A $\mathbf{H} = [2*(\gamma d/\gamma w–1)*g*c*(\cos\alpha+(c/b)*\sin\alpha)]/[Cd*(c^2/b^2)+Cl]/\delta g$

c - Benner *et alii* (2010) (*C_m* is the coefficient of inertia):

$$\mathbf{H_s}= 2*b*c*[(\gamma_d-\gamma_w/\gamma_w)*b–(\gamma_d/\gamma_w)*C_m*(u_i/g)*c]/(C_d*c^2+C_l*b^2)$$

The minimum wave heights needed to detach the original boulder “C” from the upper part of wave-cut platform in a JBS, and move boulders “A” and “B” separately from the wave-cut platform to the surf bench in SBS were calculated. The results of all hydrodynamic equations are shown in Tab. 4. Many authors used Nott’s derived equations to determine if sea storm or tsunami were responsible for boulder displacement (i.e. Mastronuzzi and Sansò, 2004; Scicchitano *et alii*, 2007; Maouche *et alii*, 2009); generally, these studies are affected by an overestimation in the calculated wave heights as results of both (ì) approximation typical of the techniques of measurement (Marsico *et alii*, 2009; Hoffmeister *et alii*, 2013) and (ìì) hydrodynamic equations (i.e. Paris *et alii*, 2009; Goto *et alii*, 2010; Bourgeois and MacInnes, 2010). Different models derived by experiments in flume permit to have a theoretical approach in which morphological and dynamic approximations are adopted at a reduced scale aimed to reproduce the reality of an impacting wave (articulation of coastline, bathymetry and topography; variety of the type of rocky coast, presence of a roughness coefficient, wave direction, etc.) (Imamura *et alii*, 2008; Matsutomi and Okamoto, 2010). On the other hand the use of the Nott’s derived equations is, at present, the only way that permits a deterministic approach which allows the use of “real” data deriving by the observation of a “real” sediment and/or form. Despite this, it is evident that among the considered equations two of them (Benner *et alii*, 2010 and Engel and May, 2012) provide very high values; the other two (Nandasena *et alii*, 2011 and Pignatelli *et alii*, 2009) provide results, although not absolutely fitting surely more compatible, which differ by no more than about 0.40-0.50 m for both considered scenarios.

5.3 Wave analysis

Having considered the orientation of the coastline and the present position of the boulders, the direction of storm waves needed to move boulders “A” and “B” was evaluated to be approximately 225°N +/- 15°. During the period 1993-2008, the buoy of the Gulf of Lion indicates an occurrence of waves coming from the 150°N-300°N directions, about 1500 of which were over 3,0 m high, and about 340 with the same wave height. Only storm waves with H> 3 m and 150°N-300°N directions were considered (Tab. 5).

Storm waves that have offshore directions between N150E and N300E, and a 0°-75°incidence range, reach the shoreline with incidence angles ranging 2°-8°(i.e.: A.S.C.E., 1974 and references therein).

From its breaking point to the coastline, the wave height first decreases slightly and then greatly increases due to the sea floor trend in the last 3 m. In fact, the sudden slope increasing of the seabed has the effect of amplifying the shoaling process, so that the wave height near the coastline becomes very close to the H_b value (i.e.: Keulegan and Paterson 1940; Sunamura and Horikawa 1974). As shown in Tab. 5, according to the Pignatelli *et alii* hydrodynamic model (2009), a minimum wave height of 5,36 m is required to detach boulder “C” in a JBS; while, to move boulders “A” and “B” from the wave-cut platform inland, minimum wave heights, respectively, of 3,97 and 3,66 m are required in an SBS. Among the recorded waves with H > 3 m, at their breaking point, 47 waves present wave heights (H_b) $\geq$ 3,66 m (Sunamura, 1992) and water depths (W_d) between 4,91 and 6,31 m (Keulegan and Patterson, 1940). While, 26 waves show at their breaking point wave heights (H_b) $\geq$ 3,97 m and water depths (W_d) between 5,39 and 6,31 m. The wave direction of all these events is between N152E and N285E. All the hydrodynamic parameters/features of the above-mentioned waves are shown in Tab. 6.

Analyzing satellite photos available since December 2003, it was already possible to observe and locate the presence of boulders “A” and “B” on the surf bench. Thus, only storm waves occurring before that date can be considered responsible for detaching and subsequently displacing the boulders. The hydrodynamic parameters, in relation to the surveyed sea floor trend and the eyewitness accounts, are absolutely compatible with the minimum Hs values of the Pignatelli *et alii* (2009) and Nandasena *et alii* (2011) models for both Joint Bounded and Sub-aerial Boulder scenarios.

5. Conclusions

The presence on the SB of boulders the position of which, thanks to eyewitness, are ascribed to the impact of a strong storm in the last two decades permits to test the validity of the hydrodynamic model in a real case of which the cause is known: the impact of storm waves. The use of digital technologies of survey – TLS and DGPS - coupled with the traditional geomorphological survey and the use of hydrodynamic equation permit to approach the study of boulder movement in coastal scenario using a quantitative–mathematical approach.

The history of the boulders was reconstructed on the basis of the 3D survey and of the presence of bio-encrustations that allow an estimate of the position of future boulder “C” emplaced in JBS at the external limit of the SB, exposed to the impact of waves. The same approach allows to estimate a phase during which the boulder “C” collapsed, completely, in the water on the WCP having a position permanently submerged during calm water. In the JBS, the application of different hydrodynamic equation suggests that a minimum storm wave of about 5,5 m high was required to scrape boulder “C” from the coast according to the Pignatelli *et alii* (2009) and of Nandasena *et alii* (2011) models. The analysis of the wave climate history of the sea in front of the studied area suggests that this value is consistent with the more energetic storms.

In a following phase, which occurred before December 2003, according to the satellite images eventually, the boulder was split into two parts, becoming boulders “A” and “B”. Just after this and during the same storm, the two boulders were separately transported inland by storm waves from the wave-cut platform to their present position on the surf bench, as evidenced by the bio-indicators and by the morphological aspects highlighted by the digital survey and by the 3D view. In this case two hydrodynamic models, Pignatelli *et alii* (2009) and Nandasena *et alii* (2011), invocate a wave of 3,5 – 4 m high to move boulders inland towards the remaining models that both require wave height of more than 6,30 m; the first values are in agreement with “the normal more energetic storms” that characterize the studied area.

To conclude, a tsunami impact, which was never recorded in the past 20 years, was not necessary to move inland boulders “A” and “B” which movements occurred before December 2003.

The hydrodynamic parameters of 47 waves (selected in the period between 1993-2008), in relation to the surveyed sea floor trend and eyewitness accounts, confirm the best fitting of the Pignatelli *et alii* (2009) and of Nandasena *et alii* (2011) hydrodynamic models with this reconstructed succession of events.

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Captions

Figure 1 – Geographical position of the studied area (from Google Earth).

Figure 2 – Examples of fracture lines in the study area; for A, B and C see the text.

Figure 3 – Joint patterns along the coast between the Plage de Bonnieu and Carro. Joints have been surveyed and mapped in four areas (Fig. a). b) Rose diagram of the strike of the 111 measured joints. c) dip of the 111 measured joints. d, e, f) aerial photos with mapped joint patterns and boulders of areas 1 to 4. Schmidt nets (lower hemisphere) show the joint planes measured in each area.

Figure 4 – Morphological features of the studied area. A: gently sloping rocky coast characterized by boulders accumulation and soil cover; B: boulders field in the surveyed area; C: cliff about 4 m height; D: notch at the foot of the cliff.

Figure 5 – Position of the buoy in the Gulf of Lion (from Google Earth).

Figure 6 – Scanned area (above) and point cloud surveyed by TLS Leica Scanstation2 (below).

Figure 7 – Schematic sketch of the surveyed area. w.c.p. = wave cut platform; s.b. = surf bench. The boulder C is located in the probable detachment area.

Figure 8 – Schematic reconstruction of the reverse procedure adopted to reconstruct the boulder "C" (above): the part "A" has undergone a rollover while the part "B" underwent a rotation. The red dotted lines represent the break's surfaces. Boulders “A”, “B” and “C” with their “a” and “b” axes (below) ; the white dotted line represents the break's surface of the boulder "C"..

Figure 9 – Morphological and biological evidence on the blocks "A" and "B". A: the surface indicated by the arrow represents the original face turned upwards; B: the break's surface of block B; C: biological evidence of *Lithophyllum bissoides* rim (white circle) on the block "A" and the break's surface indicated by the arrow; D: biological evidence of *Lithophyllum bissoides*, vermetids and barnacles on the upper surface of block "B".

Figure 10 – Probable original position and detachment zone of boulder "C" on the WCP and positions of the blocks "A" and "B" (from Google Earth, December 2003).

Figure 11 – Reconstruction of the succession of events. Phase 1: boulder "C" is in a Joint Bounded Scenario (JBS); Phase 2: boulder "C" is detached and placed on the WCP; Phase 3: the block "A" moves toward inland while turning in a clockwise direction and overturns; Phase 4: the block "B" moves inward while turning of approximately 90 ° counterclockwise.

Tables

	Number of Waves with HeightH> 3 m				
YEAR	**I Sector**	**II Sector**	**III Sector**	**IV Sector**	**Total**
1993	21	9	0	31	**61**
1994	1	20	12	23	**56**
1995	1	43	5	43	**92**
1996	16	93	12	15	**136**
1997	6	39	10	7	**62**
1998	8	6	1	20	**35**
1999	0	19	17	33	**69**
2000	14	27	13	14	**68**
2001	22	15	15	9	**61**
2002	12	49	10	7	**78**
2003	7	78	8	29	**122**
2004	3	50	6	29	**88**
2005	27	33	7	81	**148**
2006	10	30	18	21	**79**
2007	48	41	0	108	**197**
2008	14	58	21	89	**182**
TOTAL	**210**	**610**	**155**	**559**	**1534**

Table 1 –Number of events > 3 m high, per year, recorded by the buoy in the period 1993-2008.

	Highest Wave (m) per Directions			
YEAR	**I Sector H - °N**	**II Sector H - °N**	**III Sector H - °N**	**IV Sector H - °N**
1993	4,16 – 88°	3,57 – 91°	//	4,19 – 318°
1994	3,22 – 88°	4,29 – 98°	4,87 – 188°	3,94 – 320°
1995	4,32 – 90°	4,34 – 91°	3,77 – 187°	4,02 – 303°
1996	3,99 – 86°	4,57 – 146°	5,16 – 190°	4,26 – 307°
1997	3,98 – 89°	6,08 – 96°	5,07 – 187°	3,30 – 325°
1998	3,95 – 90°	3,72 – 126°	3,13 – 189°	3,78 – 314°
1999	//	5,24 – 97°	4,03 – 199°	4,07 – 294°
2000	3,83 – 90°	4,97 – 108°	4,07 – 198°	3,62 – 343°
2001	4,62 – 88°	4,60 – 91°	4,66 – 203°	3,50 – 323°
2002	4,33 – 87°	4,89 – 96°	3,55 – 195°	3,80 – 317°
2003	3,86 – 90°	6,47 – 107°	5,25 – 202°	3,77 – 352°
2004	3,79 – 1°	5,41 – 95°	3,26 – 191°	4,17 – 357°
2005	3,85 – 4°	3,54 – 105°	5,15 – 200°	4,20 – 314°
2006	3,74 – 14°	5,66 – 115°	4,30 – 197°	4,13 – 330°
2007	4,31 – 3°	4,95 – 97°	//	4,34 – 296°
2008	5,17 – 90°	6,85 – 97°	4,51 – 195°	4,19 – 300°

Table 2–Highest waves recorded by the buoy, for each year, in the period 1993-2008. H: height of wave in m; °N: wave direction.

	a axis (m)	**b axis (m)**	**c axis (m)**	**Volume* (m^3)**	**γ_d (g/cm^3)**	**Weight (t)**
Boulder A	**3,60**	**2,60**	**0,38**	**6,90**	**2,3**	**15,87**
Boulder B	**2,60**	**2,10**	**1,10**	**3,85**	**2,3**	**8,86**
Boulder C	**6,20**	**2,60**	**0,38**	**10,75**	**2,3**	**24,73**

Table 3 – Dimensional parameters of the boulders.*The boulders volume was calculated by means of the laser scanner software.

	Engel and May (2012)	Nandasena*et alii* (2011)	Benner *et alii* (2010)	Pignatelli*etalii* (2009)
	Hs (m)	H (m)	Hs (m)	Hs (m)
Boulder A (SBS)	6,35	4,58	6,25	3,97
Boulder B (SBS)	4,89	3,10	5,53	3,66
Boulder C (JBS)	5,72	5,61	6,25	5,36

Table 4 –Storm wave Hs obtained by different hydrodynamic equations for boulders A, B and C.

	Observed Period 1993 - 2008	
Wave Range Direction	**N. events with H > 3 m**	**Highest Wave in m**
150-160 °N	14	4,38
160-170 °N	11	4,35
170-180 °N	18	5,48
180-190 °N	45	5,16
190-200 °N	90	5,15
200-210 °N	19	5,25
210-220 °N	0	//
220-230 °N	0	//
230-240 °N	0	//
240-250 °N	0	//
250-260 °N	0	//
260-270 °N	1	3,23
270-280 °N	17	4,15
280-290 °N	38	4,17
290-300 °N	83	4,34
TOTAL	**336**	

Table 5 –Number of events with height > 3 m and the highest waves selected per 10° range direction recorded in the period 1993-2008.

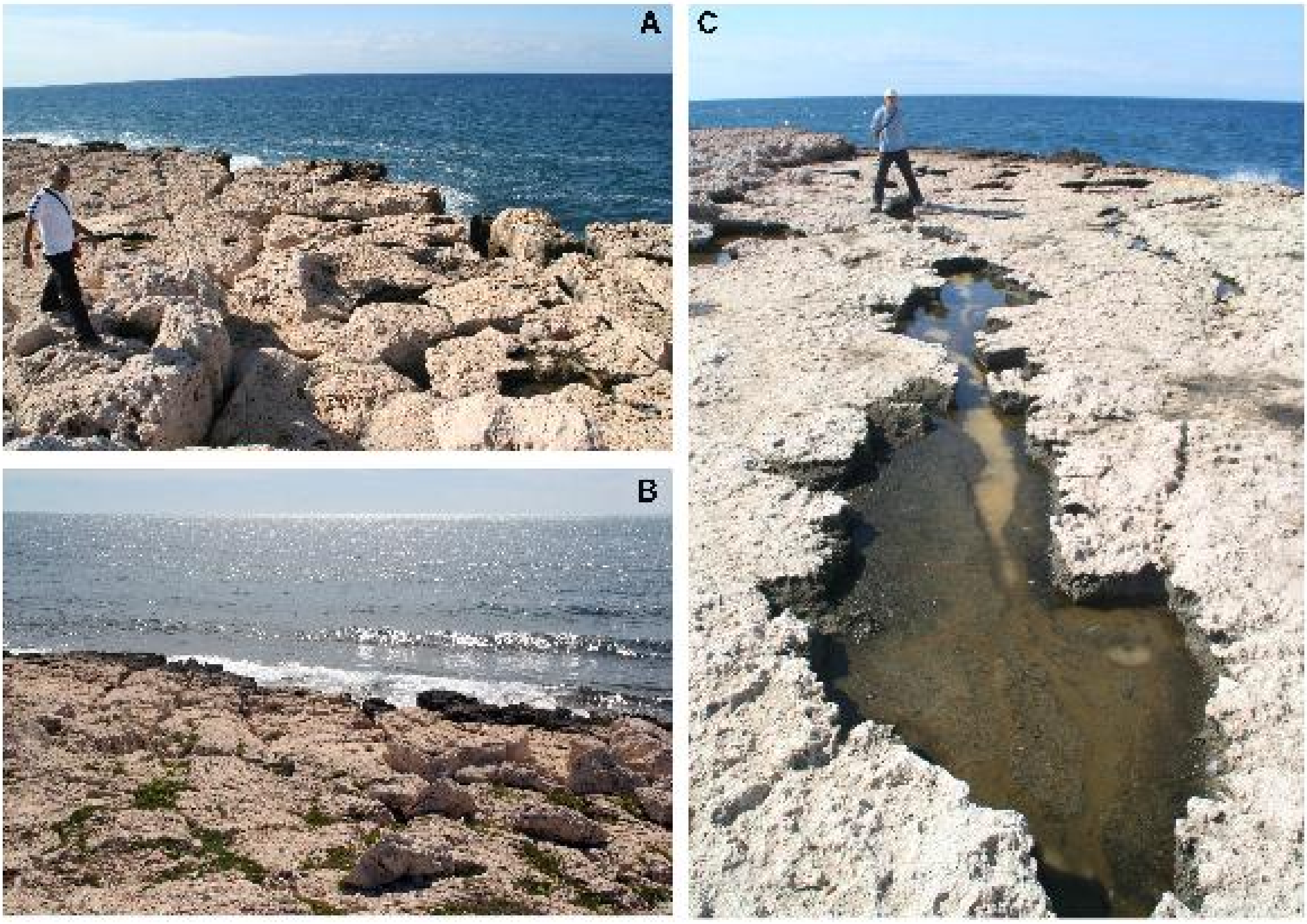
Date	**Wave Height H (m)**	**Wave Direction (°N)**	**Period (s)**	**Length Wave L_0(m)**	**Breaking Water Depth W_d (m)**	**Breaking Wave Height H_b(m)**
06/01/1994	3,85	193	8,36	109,06	4,61	3,44
06/01/1994	4,24	193	8,49	112,48	5,00	3,73
06/01/1994	4,62	192	8,95	125,00	5,47	4,08
06/01/1994	4,73	193	8,68	117,57	5,49	4,09
06/01/1994	4,70	190	8,97	125,56	5,55	4,14
06/01/1994	4,87	188	8,96	125,28	5,70	4,25
07/01/1994	3,71	197	9,11	129,51	4,68	3,49
07/01/1994	4,47	197	9,12	129,79	5,39	4,02
07/01/1994	4,66	193	9,05	127,81	5,54	4,13
23/01/1996	4,04	159	7,97	99,12	4,67	3,48
23/01/1996	4,38	152	8,23	105,70	5,04	3,76
11/11/1996	4,17	182	7,77	94,21	4,72	3,52
11/11/1996	4,46	185	8,25	106,21	5,12	3,82
11/11/1996	4,77	187	8,43	110,90	5,44	4,06
12/11/1996	3,66	185	8,29	107,24	4,42	3,30
12/11/1996	3,98	186	8,41	110,37	4,74	3,54
12/11/1996	4,33	186	8,58	114,88	5,10	3,81
12/11/1996	4,66	190	8,86	122,50	5,48	4,09
12/11/1996	4,95	190	8,99	126,12	5,78	4,31
12/11/1996	5,11	188	8,63	116,22	5,80	4,32
12/11/1996	5,16	190	8,98	125,84	5,96	4,44
03/01/1997	4,25	178	7,86	96,41	4,82	3,59
03/01/1997	4,35	190	8,38	109,59	5,06	3,78

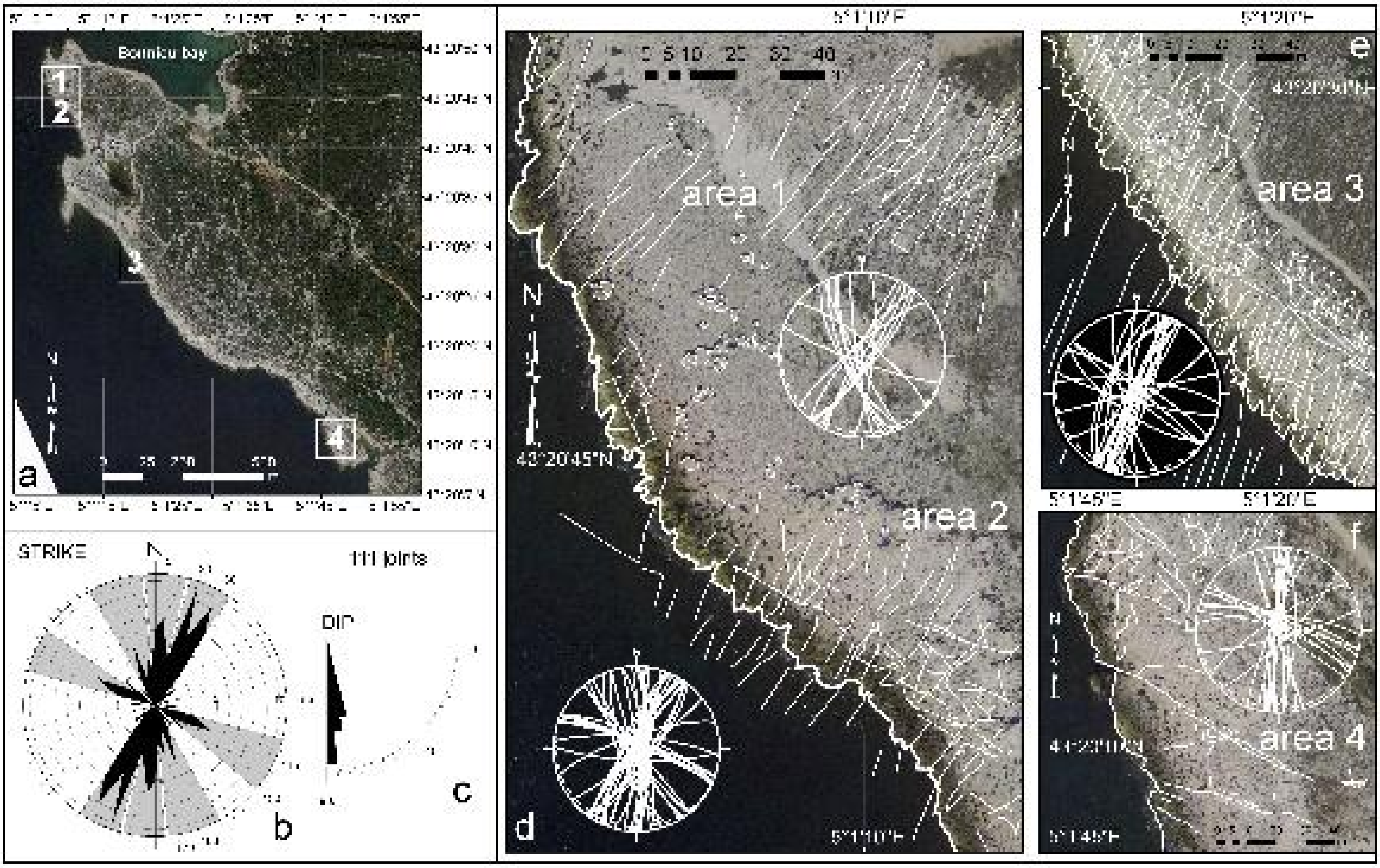
04/01/1997	3,76	196	8,91	123,89	4,68	3,49
04/01/1997	4,19	195	8,55	114,08	4,97	3,71
06/11/1997	4,55	176	7,98	99,37	5,11	3,81
06/11/1997	5,19	174	8,51	113,01	5,82	4,34
06/11/1997	5,48	173	9,17	131,22	6,30	4,70
06/11/1997	5,43	180	9,34	136,13	6,31	4,71
07/11/1997	3,47	191	9,4	137,89	4,53	3,37
07/11/1997	4,32	189	9,64	145,02	5,40	4,03
07/11/1997	5,07	187	9,54	142,04	6,06	4,52
18/12/1997	3,91	165	7,53	88,48	4,43	3,30
18/12/1997	4,07	159	7,57	89,42	4,58	3,41
18/12/1997	4,16	156	7,59	89,90	4,66	3,47
18/12/1997	4,24	155	7,63	90,85	4,74	3,53
18/12/1997	4,41	156	7,75	93,73	4,92	3,67
18/12/1997	4,35	161	7,96	98,88	4,93	3,68
24/10/1999	3,84	200	8,23	105,70	4,57	3,41
24/10/1999	4,03	199	8,33	108,28	4,77	3,55
24/10/1999	4,01	198	8,38	109,59	4,76	3,55
25/10/1999	3,69	198	8,35	108,80	4,47	3,33
28/12/1999	4,07	294	7,07	78,00	4,42	3,30
06/11/2000	3,91	198	7,63	90,85	4,46	3,33
06/11/2000	3,74	199	8,45	111,42	4,54	3,38
06/11/2000	4,07	198	8,13	103,14	4,74	3,54
02/03/2001	4,37	203	8,52	113,28	5,12	3,82
03/03/2001	3,52	201	9,33	135,84	4,56	3,40
03/03/2001	4,11	201	9,30	134,97	5,11	3,81
03/03/2001	4,66	203	9,19	131,79	5,58	4,16
31/10/2003	4,35	199	8,35	108,80	5,05	3,77
31/10/2003	4,58	201	9,42	138,47	5,58	4,16
31/10/2003	5,00	202	8,73	118,93	5,74	4,28
31/10/2003	5,05	201	9,32	135,55	5,97	4,45
31/10/2003	5,25	202	9,22	132,66	6,12	4,56
01/11/2003	3,94	198	9,54	142,02	5,02	3,74
18/01/2005	3,90	298	7,70	92,52	4,47	3,33
19/01/2005	4,05	299	8,20	104,93	4,75	3,54
02/12/2005	3,77	194	10,30	165,55	5,05	3,76
02/12/2005	4,52	197	9,00	126,40	5,40	4,03
02/12/2005	4,53	195	10,10	159,19	5,73	4,27
02/12/2005	5,15	200	9,60	143,82	6,15	4,59
02/12/2005	5,03	196	10,10	159,19	6,20	4,62
19/02/2006	3,67	198	9,20	132,08	4,67	3,48
19/02/2006	3,95	196	8,50	112,75	4,74	3,54
19/02/2006	4,09	198	9,10	129,23	5,04	3,76
19/02/2006	4,30	197	9,00	126,40	5,20	3,88
04/03/2006	3,56	206	8,90	123,61	4,49	3,35
04/03/2006	3,60	200	9,30	134,97	4,63	3,45
23/01/2007	4,08	281	8,30	107,50	4,80	3,58
23/01/2007	4,17	285	8,40	110,11	4,91	3,66
24/01/2007	3,84	291	8,20	104,93	4,56	3,40
24/01/2007	3,86	291	8,30	107,50	4,61	3,43
24/01/2007	3,91	290	8,20	104,93	4,62	3,45
24/01/2007	4,13	288	8,30	107,50	4,85	3,61
24/01/2007	4,09	290	8,40	110,11	4,84	3,61
28/05/2007	4,00	287	8,20	104,93	4,70	3,50
28/05/2007	4,16	300	8,30	107,50	4,87	3,63
28/05/2007	4,34	296	8,30	107,50	5,03	3,75
29/05/2007	3,93	297	8,10	112,39	4,61	3,44
09/12/2007	3,99	279	8,20	104,93	4,69	3,50
10/12/2007	3,75	283	8,20	104,93	4,48	3,34
10/12/2007	3,93	282	8,30	107,50	4,67	3,48

10/12/2007	4,01	279	8,30	107,50	4,74	3,53
10/12/2007	4,15	280	8,40	110,11	4,89	3,65
10/12/2007	4,17	281	8,40	110,11	4,91	3,66
11/01/2008	3,87	202	8,30	107,50	4,61	3,44
21/03/2008	3,97	277	7,80	94,94	4,56	3,40
20/04/2008	3,83	168	8,30	107,50	4,63	3,45
21/11/2008	4,04	300	8,20	104,93	4,74	3,53
21/11/2008	4,19	300	8,40	110,11	4,93	3,67
29/11/2008	4,13	196	9,50	140,84	5,18	3,87
29/11/2008	4,51	195	9,00	126,40	5,39	4,02

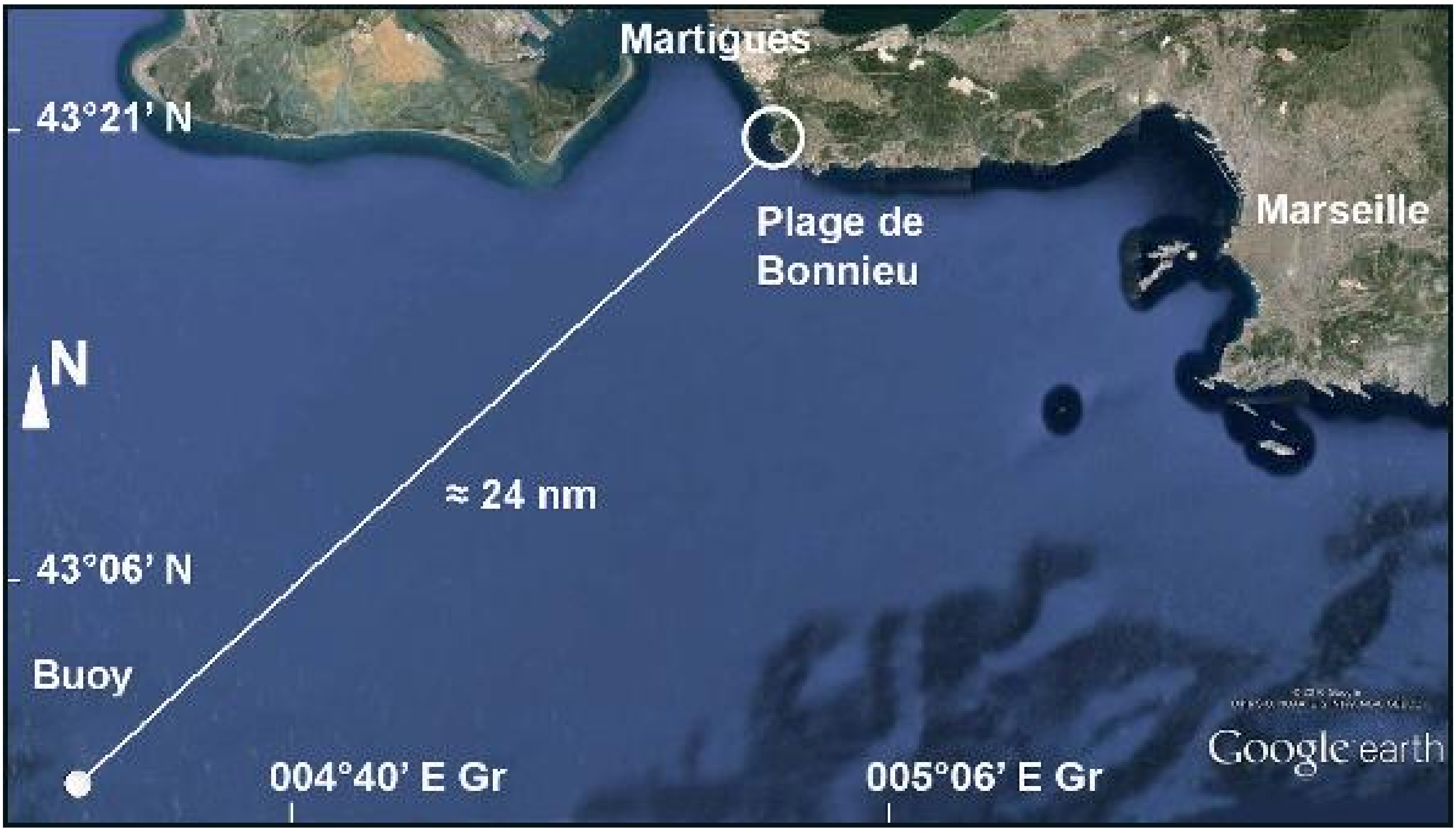
Table 6 – Hydrodynamic parameters of the events with a $H_b$prox to the minimum value (H_b>3,66m) useful to move boulders A and B. H_0 = Wave Height offshore; L_0 = Wave Length offshore; W_d = Water Depth at breaking point; H_b = Wave Height at breaking point.

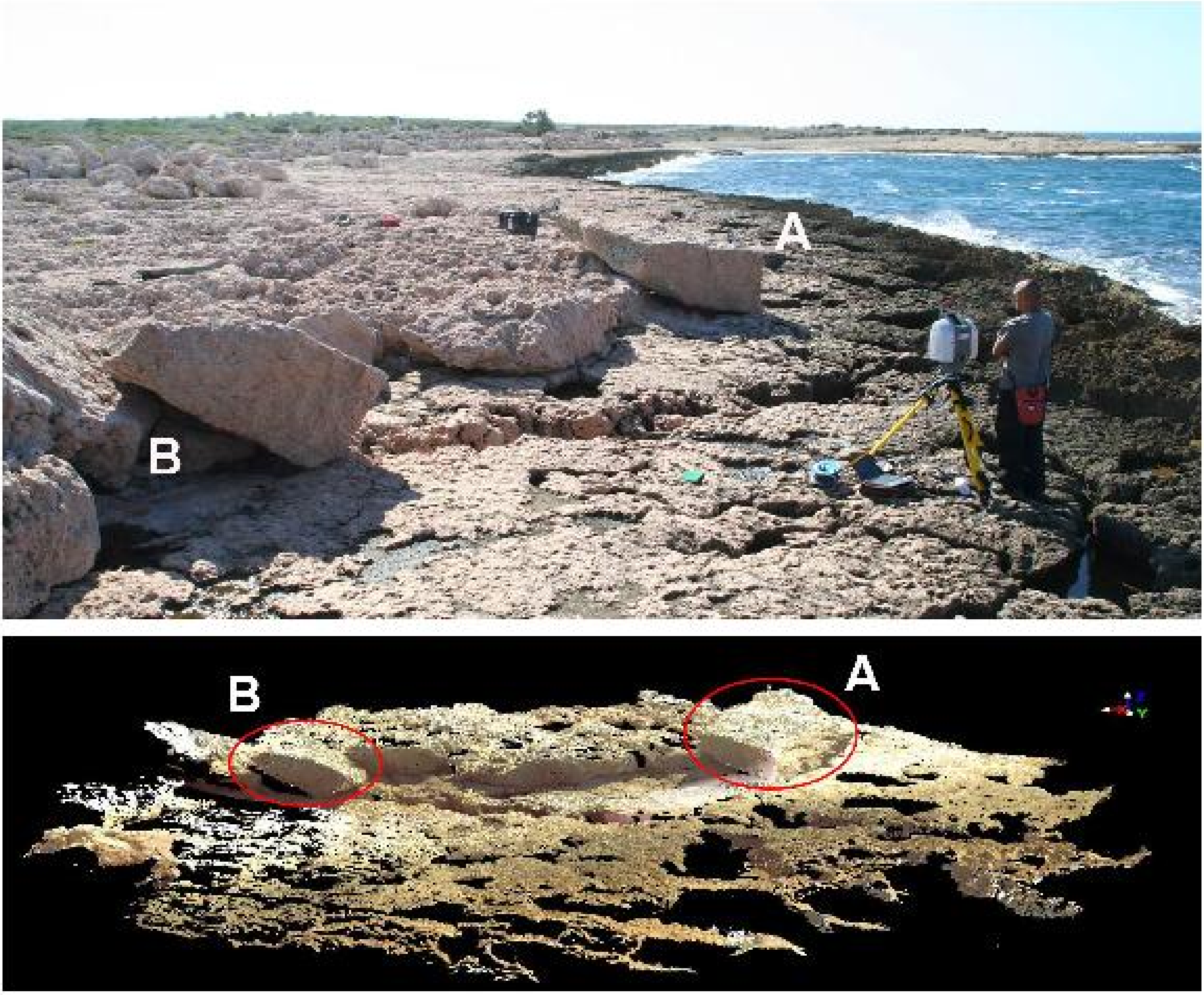

005°01’ E Gr
005°02’ E Gr
43°21’ N
Plage de Bonnieu
Carro
43°20’ N
FRANCE
Martigues
Image © 2015 Aerodata International Surveys
Image © 2015 DigitalGlobe
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2015 TerraMetrics
Google earth

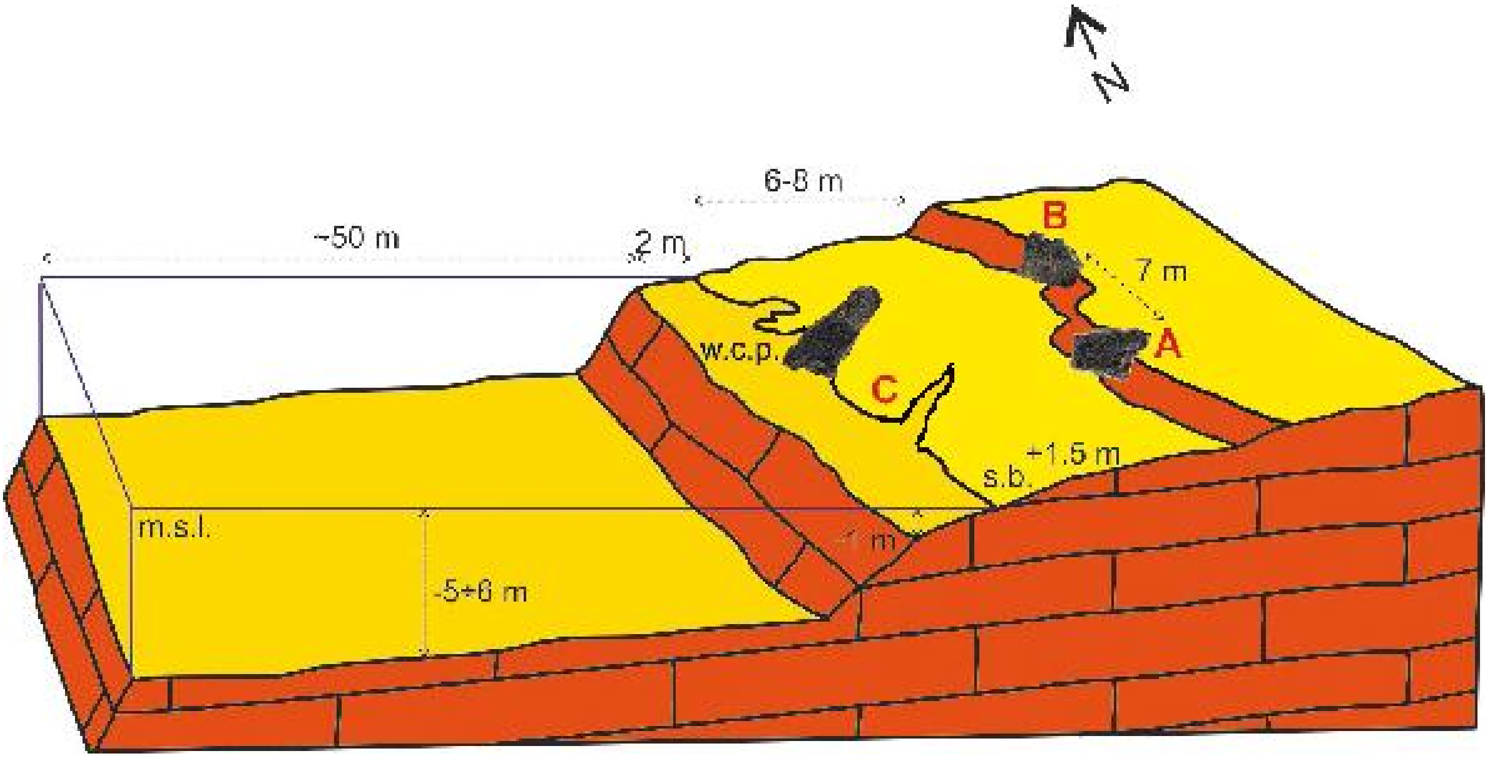

A
C
B

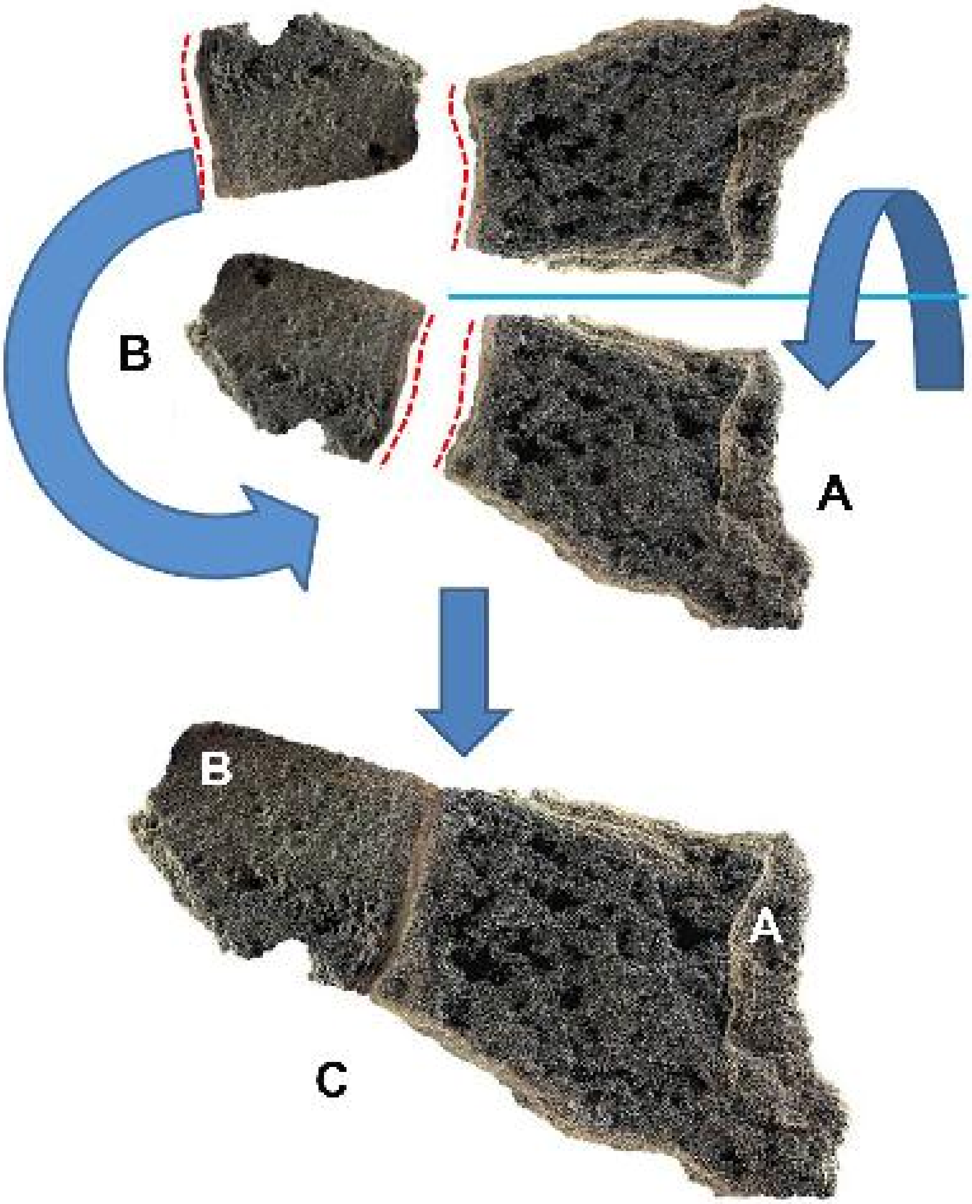

Bonnieu bay
1
2
3
4
a
N
STRIKE
N
111 joints
DIP
b
c
5°1'10"E
0 5 10 20 30 40 m
area 1
N
43°20'45"N
area 2
d
5°1'10"E
5°1'20"E
e
43°20'30"N
N
area 3
5°1'45"E
5°1'20"E
f
N
area 4
5°1'45"E

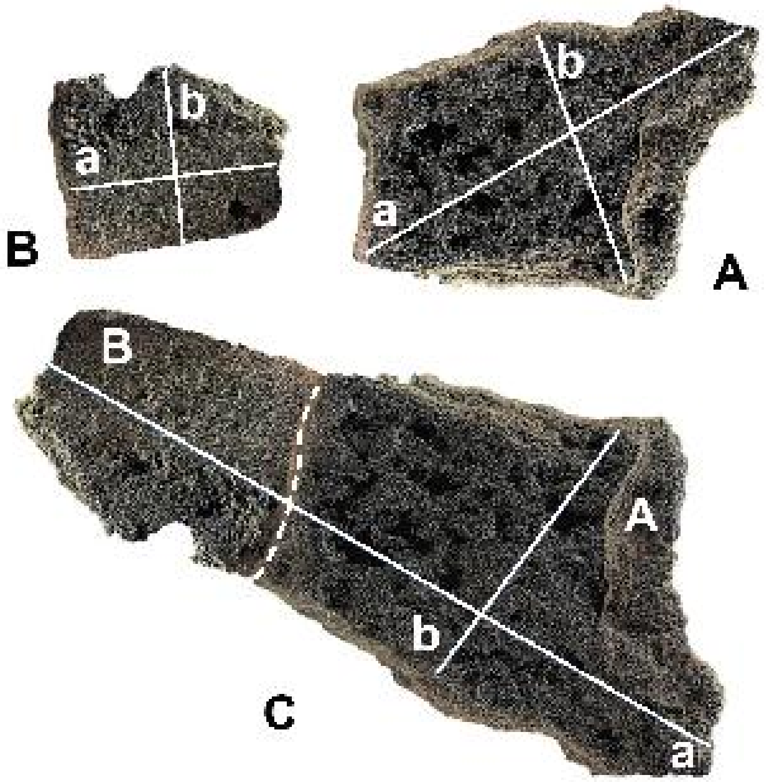

A
B
C
D


Martigues
43°21' N
Plage de
Bonnieu
Marseille
N
≈ 24 nm
43°06' N
Buoy
004°40' E Gr
005°06' E Gr
Google earth

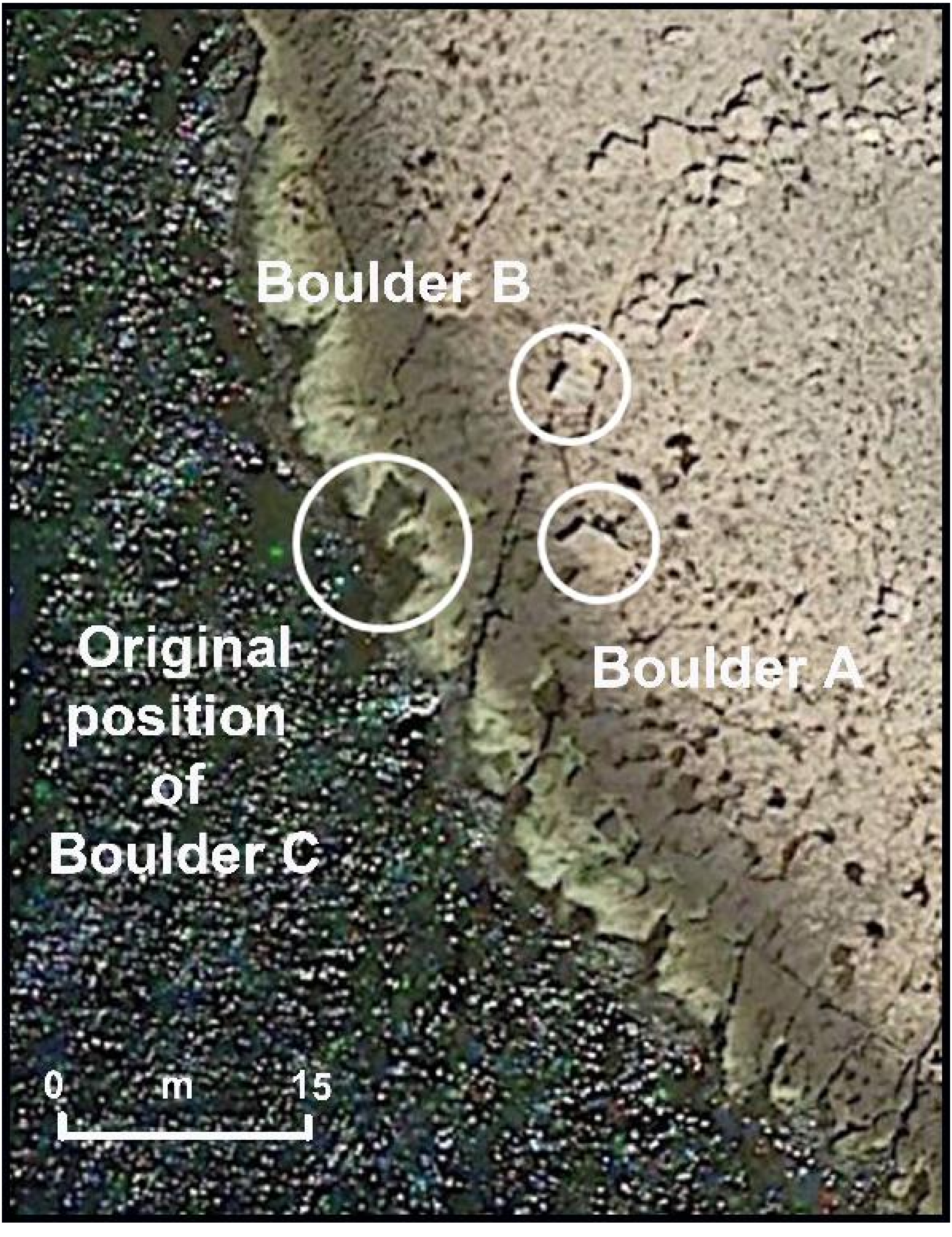

A
B
B
A

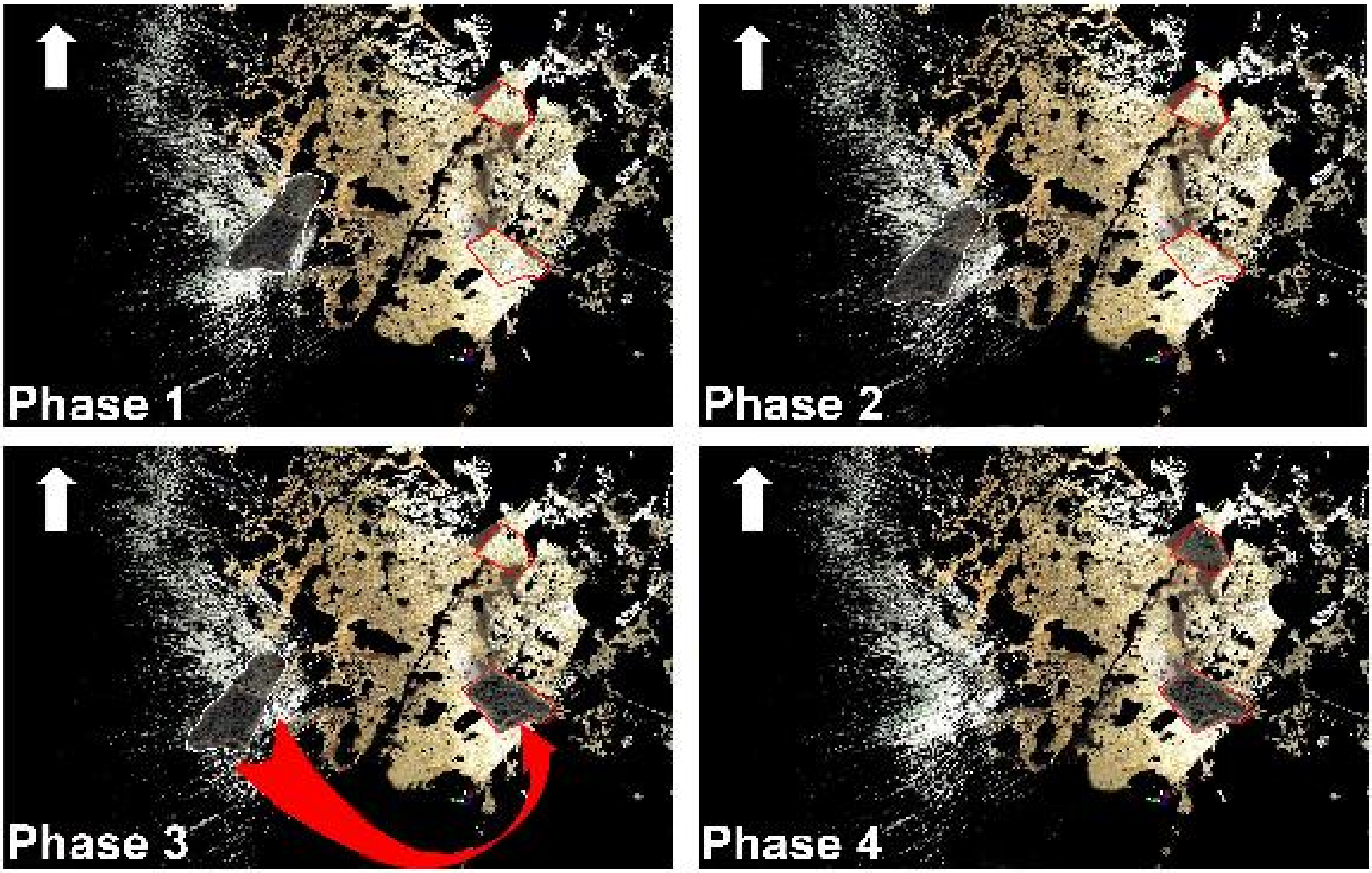

N
6-8 m
~50 m
2 m
B
7 m
A
w.c.p.
C
s.b.
+1.5 m
m.s.l.
-1 m
-5÷6 m


B
A
B
A
C


b
a
B
b
a
A
B
A
b
C
a


A
B
C
D


Boulder B
Boulder A
Original position of Boulder C
0
m
15


Phase 1
Phase 2
Phase 3
Phase 4